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PREVENTION OF DUPLEX GRAIN STRUCTURES IN CONTROLLED-ROLLED HSLA STEEL PLATE

Final Report

by

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EXECUTIVE SUMMARY

The possible causes of duplex grain structure were investigated and means of minimizing or eliminating its occurrence were explored by three different approaches. These were (i) simulation of rolling by torsional deformation; (ii) modeling of dynamic recrystallization; and (iii) modeling of the dynamic γ-to-α transformation. The effects of the following factors on the formation of duplex grain structures were explored: the reheated grain size, the roughing and finishing temperatures, the number of roughing and finishing passes, the strain per pass and the cooling rate after finishing. The considerations involved in avoiding mixed grain structures while producing fine grain sizes are described.

COMMENT EVITER LA FORMATION DE STRUCTURES DUPLEX AU COURS DU LAMINAGE CONTROLE DES ACIERS MICROALLIES

RESUME

Les causes possibles d'une structure duplex ont été étudiées et les moyens de minimiser ou d'éliminer la formation ont été explorés par trois approches différentes. Celles-ci étaient: (i) la simulation du laminage par une déformation en torsion; (ii) la modélisation de la recristallisation dynamique; et (iii) la modélisation de la transformation dynamique $\gamma \rightarrow \alpha$. L'influence des paramètres suivants sur la formation de structures duplex a été analysée: la taille de grain après réchauffage, les températures de dégrossissage et de finition, le nombre de passes au cours du dégrossissage et de la finition, la déformation par passe et la vitesse de refroidissement après la finition. Les moyens d'éviter une structure et d'obtenir ainsi une taille de grain fine sont décrits.

PREVENTION OF DUPLEX GRAIN STRUCTURES IN CONTROLLED-ROLLED HSLA STEEL PLATE

FINAL REPORT

In this final report, the contract work carried out during the preceeding three years will be reviewed. As indicated in the overall objective listed below, the possible causes of duplex grain structure were investigated and means of minimizing or completely preventing its occurrence were explored.

OVERALL OBJECTIVE:

On behalf of CANMET, Energy, Mines and Resources Canada, to conduct experimental research to determine the causes of the undesirable duplex grain structure which develops during the controlled rolling of microalloyed high strength steels, and to examine processing methods of preventing or minimizing the duplexing of the steel microstructure.

PHASE I Microstructural Characterization of Simulated Rolling Deformation: In a base microalloyed steel composition, examine and characterize the development of austenite microstructure and the austenite-to-ferrite transformation in simulated rolling deformation.

PHASE II Examination of Causes and Prevention of Duplex Microstructure: Examine the effects of starting austenite grain size, and the effects of austenite deformation and grain growth, in the complete, partial, and non-recrystallization temperature ranges, on the above characteristics. Clarify how duplex grain structure is developed, and determine guidelines for thermomechanical treatment to minimize or prevent the development of duplex grain structure.

PHASE III Specific Microalloying Additions: Examine the effects of specific microalloying additions to the base composition on the development of austenite microstructure during simulated rolling deformation, and recommend thermomechanical treatment to minimize duplex microstructure.

The causes of the formation of mixed grain sizes determined through this work, can be summarized under the following major headings:

(i) Mixed initial grain sizes: In this category are factors such as the reheating of the material into temperature regions in which incomplete carbonitride dissolution occurs resulting, particularly in HSLA steels, in non-uniform initial grain sizes.

(ii) Abnormal grain growth: When light reductions are applied at high temperatures, some of the grains can grow abnormally. These large grains cannot always be eliminated in subsequent rolling.

(iii) Incomplete (static) recrystallization: During the interpass period following a rolling reduction, if the temperature is high enough, recrystallization goes to completion, producing a fairly uniform grain structure. This is desirable during roughing, and leads to grain refinement through one or more cycles of recrystallization. Alternatively, at low rolling temperatures, recrystallization does not even begin. This is what happens during low temperature finishing; it is responsible for a pancaked austenite grain structure. However, at intermediate temperatures, incomplete recrystallization takes place during the interpass time; such an arrested 'transformation' results in a mixed grain structure which transforms on cooling into a mixed ferrite grain structure.

(iv) Incomplete dynamic recrystallization: If dynamic recrystallization is initiated during deformation, and the strains are not large enough to establish steady state conditions of flow, it leads to the production of mixed grain structures.

(v) Inhomogeneous deformation and recrystallization (deformation band formation in coarse grains): Special considerations apply when the initial or recrystallized grain size is coarse and deformation bands form during rolling. Fine austenite grains are then produced in the bands, which transform into duplex grain structures.

(vi) Dynamic austenite to ferrite transformation: When steel is rolled just below the Ae_3 temperature and subjected to continuous cooling, the austenite to ferrite transformation is initiated at higher temperatures than predicted from equilibrium considerations (i.e. from the isothermal diagram). The ferrite formed at higher temperatures as a result of deformation is coarser than that formed at lower temperatures from the deformed austenite. This also leads to a form of duplexing.

Three different approaches were used to distinguish between the effects of the above factors. The secondary objective of demonstrating how duplex grain structures can be avoided was also attained in this way. These methods are described below and a summary of the principal results obtained is also presented.

I. SIMULATION OF ROLLING BY TORSIONAL DEFORMATION

This project was carried out by Lakis Mavropoulos. Most of the work is described in his M.Eng. thesis of 1983 (Ref. 1), copies of which have been forwarded to CANMET. The experimental findings he has produced since his thesis was submitted are reviewed here and in the accompanying figures.

A 'ternary' steel prepared at CANMET containing 0.09% C, 1.19% Mn, 0.30% Mo, 0.035% Nb and 0.115% V was selected. Each sample was reheated at 1200°C for 20 minutes which resulted in an initial uniform but coarse austenite grain size of approximately 250-300 μm. Following reheating, a standard cooling cycle not too different from that used in plate rolling was applied. The number of roughing passes was varied as well as the strain per roughing pass and roughing strain rate. Various strains, strain rates and pass sequences were employed for finish rolling. In addition, the effect of cooling rate after the last pass was also investigated. The findings can be summarized as follows:

ROUGHING STAGE

1. Effect of deformation temperature on the austenite grain size: When the initial grain size, strain and strain rate are kept constant and the deformation temperature is decreased, finer austenite structures are produced. This can be attributed to the influence of the progressively higher dislocation density on the nucleation and growth kinetics of the recrystallized grains.

2. Influence of the number of roughing passes on the austenite grain size: When the number of roughing passes is increased, the austenite grain size is decreased. The recrystallized grain size, however, cannot be indefinitely refined; in the present experiments, the two final passes (at 1030 and 1050°C) led to the greatest reduction in grain size. Additional passes at higher temperatures only produced a marginal reduction of the grain size; nevertheless, the homogeneity of the grain structure was improved.

3. Effect of the number of roughing passes on the ferrite grain size: For a fixed finishing schedule in the 'no-recrystallization' range, more uniform ferrite structures are produced when the number of roughing passes is increased. When the recrystallized austenite grain size is increased above 50 μm, increasingly non-uniform ferrite structures are produced.

Figure 1: Austenite grain structure of torsion specimen after reheating at 1200°C for 20 min. (x 80).

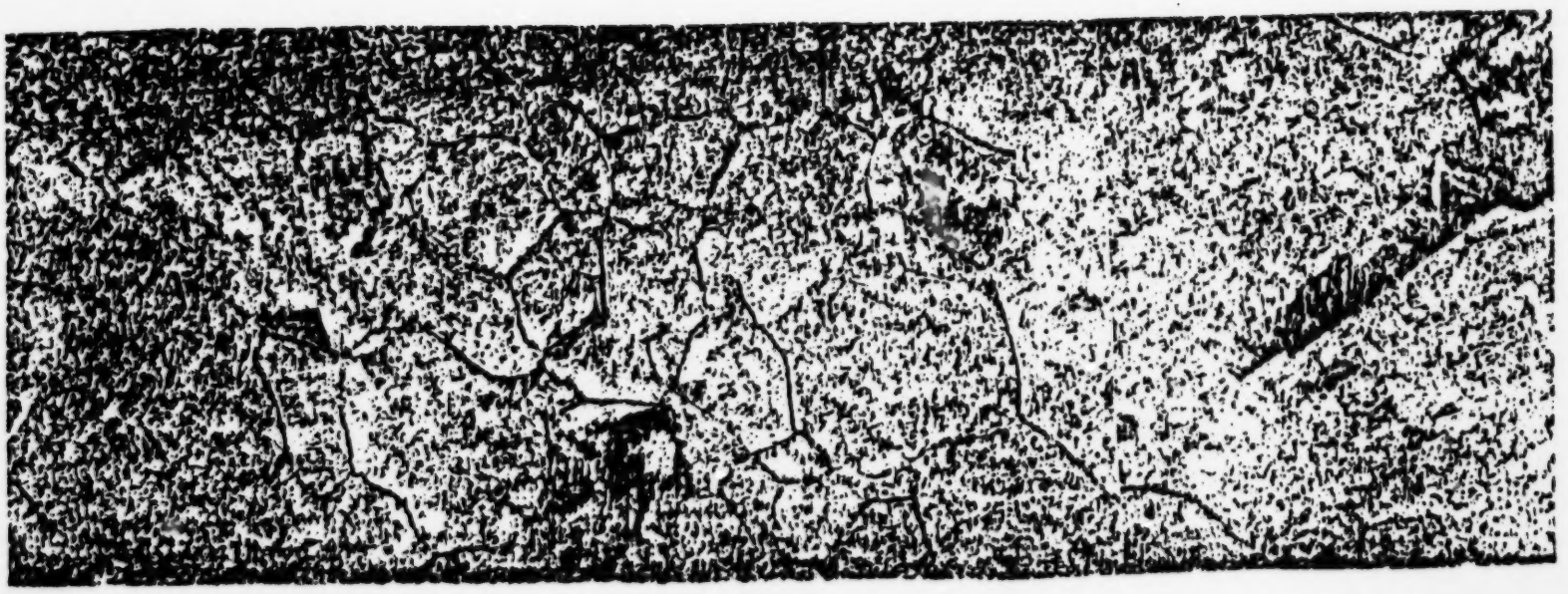

Figure 2: Austenite grain structure of torsion specimen after 5% strain and 60 second hold at 1200°C. Abnormal grain growth is observed in some regions. (x 80)

Figure 3: Austenite grain structure of torsion specimen after 10% straining and a 60 second hold at 1200°C. The recrystallized grain structure is more uniform in this case than after 5% strain, Fig. 2. (x 80)

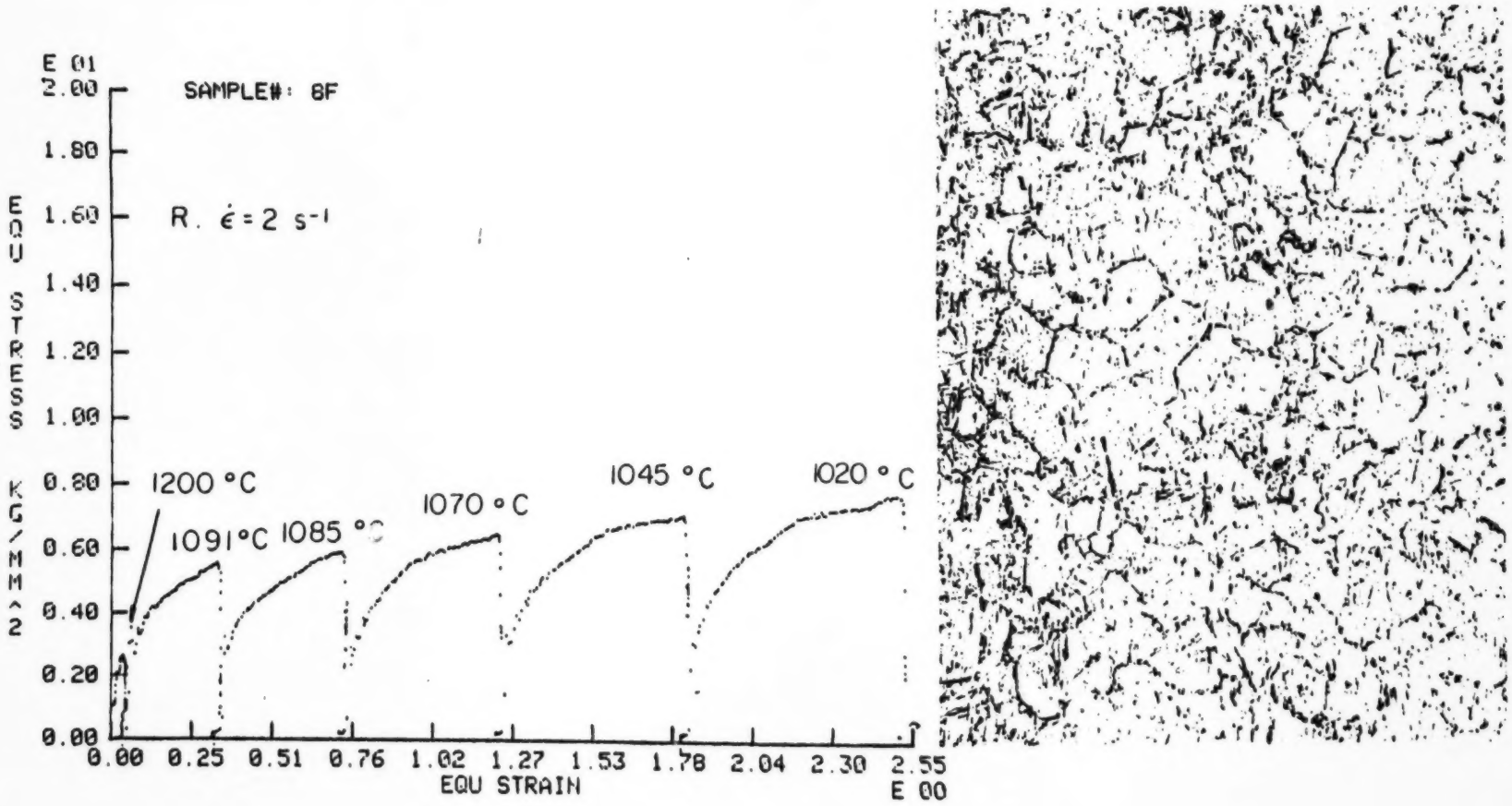

Figure 4: The flow curves and the resulting microstructure following a light reduction (5%) and five regular reductions. The duplex grain structure (Fig. 2) after the light reduction is eliminated by complete recrystallization during the subsequent roughing interpass times. (x 200)

4. Influence of deformation per pass: Both the austenite and the ferrite grain sizes decrease when larger reductions per pass are applied. This can be ascribed to the way in which deformation increases the number of nucleation sites for static recrystallization.

5. Effect of light reductions: Mixed grain structures are introduced when light reductions (5 to 10% strain) are effected at high temperatures. When sufficient deformation passes are applied subsequently, the duplex structures are eliminated. As an example, in Fig. 1 (attached), the initial austenite grain structure of a torsion specimen reheated for 20 minutes at 1200°C is shown. It is coarse but uniform, with an average grain size of 250-300 μm. The austenitic structures resulting from a single deformation of (i) 5 and (ii) 10% at 1200°C followed by a 60 second hold at temperature are shown in Figs. 2 and 3, respectively. A mixed microstructure is seen in the sample deformed 5% and a nearly equiaxed microstructure in the sample strained 10%. The mixed microstructures introduced in the early stages of the controlled rolling process were eliminated by the use of subsequent roughing passes which permitted complete static recrystallization to take place after each roughing pass. The flow curves and the resulting microstructures are shown in Fig. 4 and it is evident from the latter that the grain size is uniform.

FINISHING STAGE

1. Influence of finishing temperature on ferrite grain size: Lower finishing temperatures result in the formation of finer ferrite grains. This correlation is valid down to finishing temperatures of 755°C, with which a grain size of 6-7 μm is associated. A further decrease in the rolling temperature in the range 755 to 710°C does not lead to a further reduction in grain size. (Here 710°C is the estimated Ar_3 temperature for the experimental material during deformation and while undergoing cooling at the present rates.)

2. Rolling below the Ar_3 temperature: When finishing temperatures below 710°C are employed, the average ferrite grain size is reduced to 3-4 μm.

The grain structure, however, is inhomogeneous under these conditions. This inhomogeneity is most likely due to the dynamic (deformation assisted) austenite to ferrite transformation which occurs at higher temperatures than in the absence of deformation, i.e. under static conditions. Because these ferrite grains are formed at higher temperatures, they are larger than those produced from the static transformation of pancaked austenite grains at the lower temperatures. The formation of ferrite at two different temperatures (i.e. the 'dynamic' and 'static' population) results in mixed grain sizes.

3. Effect of amount of deformation: Applying larger strains during finishing (in the no-recrystallization domain) produces finer ferrite grain structures. This is because there is an increase with strain in both the surface to volume ratio (Sv) of the austenite grains as well as the density of deformation bands, creating a greater number of nucleation sites for phase transformation.

EFFECT OF COOLING RATE AFTER FINISHING

When the recrystallized grain size, strain rate and finishing temperature are held constant, the austenite/ferrite grain size ratio can be increased by accelerating the cooling rate after finishing.

Mavropoulos presented a paper at the AIME Fall Meeting in Philadelphia in October, 1983 (and also at the June 1983 Canadian Metal Physics Conference in Kingston, Ont.). He is preparing a manuscript for publication based on this research.

II. MODELING OF DYNAMIC RECRYSTALLIZATION

A new, and now widely accepted model of dynamic recrystallization was developed at McGill during this contract by Dr. T. Sakai and co-workers. Although the funding from CANMET was kept to a minimum, it was essential to the completion of this sub-project, and the critical support received is gratefully acknowledged. The model is based on a preliminary one originated by Dr. Sakai at the University of Electrocommunications in Tokyo; it was subsequently refined and amplified during his year and a half long sabbatical visit at McGill.

Relevance to this contract:

Dynamic recrystallization is reported to occur only rarely during plate rolling; however, it can take place if one or more of the following conditions apply:

(i) Rolling is performed at relatively high temperatures (where the critical strain for the onset of dynamic recrystallization ε_c is small).

(ii) Large reductions (greater than ε_c) are applied.

(iii) Interpass times are too short for any substantial recrystallization to take place, leading to the accumulation of a dislocation density in excess of that associated with ε_c.

All three of these conditions can be satisfied for rod or bar rolling in conventional mills, and (iii) is likely to hold for strip rolling if the temperature is sufficiently high. As a general rule, the higher the alloy concentration, the larger is ε_c, and therefore, the less likely is dynamic recrystallization to occur. More significant, however, is the recrystallization strain ε_x, i.e. the strain for the completion of recrystallization, once initiated. As the total strain required for the spreading of dynamic recrystallization throughout the material ($\varepsilon_c + \varepsilon_x$) is quite large,

even if it is nucleated, dynamic recrystallization is unlikely to go to completion under industrial conditions. Because of the characteristics of the 'necklacing' process, this invariably leads to the formation of duplex grain structures.

The individual features of this new model will now be described briefly.

1. The dynamic recrystallization model: According to the model, described in detail in Ref. 2, dynamic recrystallization can lead to either grain coarsening or grain refinement. These processes are associated with the multiple and single peak types of flow curve, respectively. The transition from one to the other occurs at $D_o = 2D_s$, where D_o is the initial grain size and D_s is the dynamically recrystallized grain size. When $D_o > 2D_s$, grain refinement occurs by a mechanism known as 'necklacing', i.e. nucleation starts at the austenite grain boundaries and progresses in 'strands' towards the interior of the coarse reheated grains as a result of continued straining. This type of mechanism can operate under industrial conditions, although, because of the large value of ε_x, it is unlikely to attain the grain interiors, so that a duplex grain structure generally results. Because the condition $D_o < 2D_s$ is rarely satisfied, the grain coarsening type of recrystallization is not expected to occur in steels under industrial conditions of rolling.

2. Dynamic recrystallization in microalloyed steels: The Sakai critical grain size model was verified in a 0.115% V, a 0.035% Nb and a 0.040% Nb - 0.30% Mo microalloyed steel, under conditions of both the solute retardation of recrystallization as well as when there is an additional component of precipitate retardation (Ref. 3). Relative to a plain C steel, additions of the microalloying elements increase the critical strain for recrystallization; nevertheless, the model is valid for these materials as well. The likelihood of forming a duplex grain structure due to incomplete dynamic recrystallization is considerably reduced as the onset of recrystallization is delayed by the microalloy additions.

3. Dynamic recrystallization during transient deformation: The influence of an increase or a decrease in strain rate on dynamic recrystallization after deformation into the steady state region was investigated in a 0.115% V microalloyed steel (Ref. 4). Following an increase in strain rate, the single peak (grain refinement) type of recrystallization was observed; by contrast, after a strain rate decrease, the multiple peak (grain coarsening) type of behavior was displayed. The critical condition at which the stress - strain curve changed from the multiple to the single peak type was $D_{s1} = D_{s2}$ (where D_{s1} and D_{s2} are the stable dynamically recrystallized grain sizes before and after the strain rate change, respectively). This differs from the critical condition for the annealed structure ($D_o = 2D_s$). In this paper (Ref. 4), the grain size based model for dynamic recrystallization was extended to apply under conditions where the strain rate is increasing continuously, as in industrial rolling schedules.

4. Influence of coarse grain structures on dynamic recrystallization: The influence of very large grains on dynamic recrystallization was investigated in OFHC (oxygen free high conductivity) and ETP (electrolytic tough pitch) copper (Ref. 5). (These materials were selected as models for austenite because they do not undergo a phase transformation during cooling.) In this study it was noted that, as the initial grain size is increased, the density of deformation bands also increases. These bands are additional nucleation sites for dynamic recrystallization (beyond those associated with the grain boundaries); as a result, the effective initial grain size D_o^* relevant to the critical condition $D_o = 2D_s$ decreases in the presence of the bands. In terms of steel rolling, this indicates that when large initial grain sizes are present, as is observed after reheating to relatively high temperatures, or in the absence of grain refiners such as Ti, the deformation bands that form can act as nucleation sites for both static and dynamic recrystallization. This, in turn, can lead to duplex grain structures (unless, because of the large strains, the deformation bands are uniformly distributed).

5. Effect of mode of deformation on grain refinement: The effect of test method on the transition from multiple to single peak dynamic recrystallization was reviewed in Ref. 6. It is demonstrated here that the 'intersection stress' at which ε_c and ε_x are equal depends on the mode of deformation employed; torsion, tension, compression, etc. In the Luton and Sellars model of dynamic recrystallization, it was assumed that the transition from single to multiple peak type flow occurs at $\varepsilon_c = \varepsilon_x$. In the new Sakai model, this conclusion is shown to be invalid. The discrepancy is explained in terms of factors such as the amount of flow localization, the presence of stress gradients and friction, and the difficulty of determining the surface shear stress from torque data (in torsion testing). These depend on the test technique employed and affect the evaluation of ε_c and ε_x, thus modifying the interpretation of experimental data.

6. Reviews of dynamic recrystallization: The model itself and the above variations are described in an Overview in Acta Metallurgica (Ref. 7) and in another invited publication (Ref. 8). Although this work has come to an end at McGill, research on further ramifications of the model (eg. an extension to the flow of superplastic materials) is being continued by Prof. Sakai and his students in Japan.

III. MODELING OF THE DYNAMIC γ TO α TRANSFORMATION

The influence of deformation on the austenite to ferrite transformation is being studied by E. Essadiqi on a plain C, a 0.30% Mo, a 0.07% Al and a 0.12% Ti steel. Results are currently available for the first two materials (Ref. 9). In both of these, when deformation is performed at temperatures below the Ae_3 temperature (determined by dilatometry at CANMET with the kind assistance of Dr. L. Collins), deformation moves the PF_s (polygonal ferrite start) curve to the left, i.e. to shorter times, by approximately an order of magnitude. This is attributed to the increase in the ferrite nucleus density associated with the deformation of the austenite grain boundaries (and with the formation of deformation bands in the grain interiors). Predictions based on the static TTT (time-temperature-transformation) curves suggest that no ferrite will form during the typical

interpass times involved in the low temperature finishing of these steels (e.g. at 800°C in the Mo steel). The present results indicate on the other hand that some ferrite will form dynamically under these conditions. This strain-induced ferrite is likely to be coarser than that formed from the pancaked austenite because the latter transforms at lower temperatures. As indicated above, this is a further source of mixed ferrite grain structures.

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